Decadal changes in global ocean chlorophyll

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[1] The global ocean chlorophyll archive produced by the CZCS was revised using compatible algorithms with SeaWiFS. Both archives were then blended with in situ data to reduce residual errors. This methodology permitted a quantitative comparison of decadal changes in global ocean chlorophyll from the CZCS (1979–1986) and SeaWiFS (1997–2000) records. Global spatial distributions and seasonal variability of ocean chlorophyll were similar, but global means decreased over the two observational segments. Major changes were observed regionally: chlorophyll concentrations decreased in the northern high latitudes while chlorophyll in the low latitudes increased. Mid-ocean gyres exhibited limited changes. The overall spatial and seasonal similarity of the two data records suggests that the changes are due to natural variability. These results provide evidence of how the Earth's climate may be changing and how ocean biota respond. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4215 Oceanography: General: Climate and interannual variability (3309); 1635 Global Change: Oceans (4203); 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689)

1. Introduction

[2] The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) has produced the first multi-year time series of global ocean chlorophyll observations since the demise of the Coastal Zone Color Scanner (CZCS) in 1986. Global observations from 1997–2000 by SeaWiFS combined with observations from 1979–1986 by the CZCS should in principle provide an opportunity to observe decadal changes in global ocean chlorophyll. However, incompatibilities between algorithms have so far precluded quantitative analysis. We have developed and applied compatible processing methods for the CZCS [*Gregg et al.*, 2002], using recent advances in atmospheric correction and consistent bio-optical algorithms to enhance the CZCS archive to comparable quality with SeaWiFS. Even with careful application of modern methodologies, there remain residual errors deriving from assumptions of atmospheric and oceanic optical behavior. We applied blending methodologies [*Gregg and Conkright*, 2001], where in situ data observations are merged with the satellite data, to reduce residual errors. These re-analyzed, blended data records provide maximum compatibility and permit, for the first time, a quantitative analysis of the changes in global ocean chlorophyll from the early-to-mid 1980's to the present.

2. Methods

[3] Reanalyzed CZCS chlorophyll data (Jan 1979–Jun 1986) [*Gregg et al.*, 2002] and Version 3 SeaWiFS data (Sep 1997–Dec 2000) were averaged to produce seasonal means at 1° spatial resolution, and were then blended with in situ chlorophyll data [*Gregg and Conkright*, 2001]. In statistical analyses of these data sets, we excluded comparisons in the North Pacific, North Atlantic, and Antarctic basins poleward of 40° in local autumn and winter, because of sparse sampling by the CZCS. These were the only places and times when the lower density sampling of the CZCS was important in the comparison. Basin and global means were areally-weighted for both satellite data sets and only co-located observations were used, to further minimize problems associated with low sampling density by the CZCS. Coastal observations (where bottom depth $\leq$200 m) were excluded from the analysis.

[4] Sea surface temperature (SST) and surface mean wind stress data were obtained from the NOAA/National Center for Environmental Prediction (NCEP) Reanalysis Project. The data were averaged over the two observational segments corresponding to the CZCS and SeaWiFS. Only data co-located with the ocean color data were used in the means.

3. Global and Basin Scale Decadal Changes in Blended Ocean Chlorophyll

[5] Blended satellite/in situ observations indicated that global ocean chlorophyll has decreased since the CZCS data record (Table 1). The decreases ranged from about 9% in autumn (Oct–Dec) to nearly 11% in summer (Jul–Sep). No significant change was observed in winter (Jan–Mar) or spring (Apr–Jun). Seasonal temporal patterns between the blended satellite chlorophyll records were similar, indicating a global maximum in spring/summer and a minimum in winter/autumn. The annual mean global change was −6.1% from the early 1980's to the present.

[6] Much of the global decrease was due to changes in the high latitudes (Figure 1). Blended SeaWiFS data were more than 10% lower than blended CZCS in the North Pacific and Atlantic basins in summer (Figure 1). The southern mid-ocean basins, South Indian, South Pacific, and South Atlantic, all exhibited significant decreases in blended chlorophyll in spring and summer, to nearly 28% in the South Pacific.

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Table 1. Global ocean chlorophyll concentrations (mg m^{-3}) and standard deviations from the blended CZCS record (1979–1986) and the modern blended SeaWiFS record (1997–2000), and the percent change (SeaWiFS-CZCS). *An asterisk indicates statistical significance at P < 0.05.

	Winter (Jan–Mar)	Spring (Apr–Jun)	Summer (Jul–Sep)	Autumn (Oct–Dec)
CZCS	0.232±0.359	0.250±0.402	0.288±0.431	0.242±0.412
SeaWiFS	0.225±0.309	0.245±0.375	0.257±0.347	0.221±0.296
% difference	−2.8	−2.1	−10.7*	−8.6*

[7] The low latitude oceanographic basins, in contrast, generally exhibited an increase in chlorophyll from the CZCS period (Figure 1). Three of these basins (North Indian, Equatorial Indian, Equatorial Atlantic) showed major increases for the blended SeaWiFS. An exception was the equatorial Pacific in winter, summer, and autumn.

4. Synoptic Scale Decadal Changes in Blended Ocean Chlorophyll

[8] Figures 2 and 3 depict the synoptic scale (100–1000 km) blended chlorophyll distributions from 1979-to-mid-1980's (blended CZCS) and the present (blended SeaWiFS). The overall distributions were remarkably similar: the extent, location, and shape of the global ocean mid-ocean gyre regions, the equatorial upwelling regions, and the sub-polar frontal regions exhibited a large degree of commonality between the two observational time segments. This similarity of global scale patterns was not apparent in the previously available versions of the CZCS [*Gregg et al.*, 2002]. Its presence in the re-analyzed data suggests the validity and compatibility of the two archives, and supports the quantitative decadal comparison.

[9] There are indications of major decadal changes in the intercomparisons. Chlorophyll in the North Pacific was vastly reduced in summer from the CZCS to the SeaWiFS records. The changes were associated with changes in wind stresses and SST. Mean spring scalar wind stresses decreased about 8%. Summer SST's were warmer by about 0.4°C. These results correspond with increased 300-m volume mean ocean temperatures from the 1980's to 1997, where an increase of about 0.3°C occurred in the extended North Pacific basin (equator to pole) [*Levitus et al.*, 2000]. Colder temperatures and higher wind stresses can produce deeper convective mixing and increased nutrient supply to support higher spring and summer chlorophyll concentrations, which is consistent with the findings here for the CZCS in the 1980's. Warmer SST's and reduced wind stresses can produce shallower mixed layers, leading to reduced nutrient entrainment, and reduced spring and summer chlorophyll. This supports the observations of SeaWiFS here.

[10] These decadal patterns in chlorophyll in the North Pacific may be related to the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997]. Positive PDO is characterized by cold ocean surface temperatures in the central and western North Pacific. The PDO entered positive phase in 1977 [*Mantua et al.*, 1997]. There is recent evidence of reversed phase, beginning near the launch of SeaWiFS (mid-1997) [*Hunt and Tsonis*, 2000] or perhaps more recently [*Schmidt and Webb*, 2001].

[11] A similar reduction in chlorophyll of about 14% was apparent in summer in the North Atlantic from the 1980's to the present (Figure 1). This was due to massive reduction in

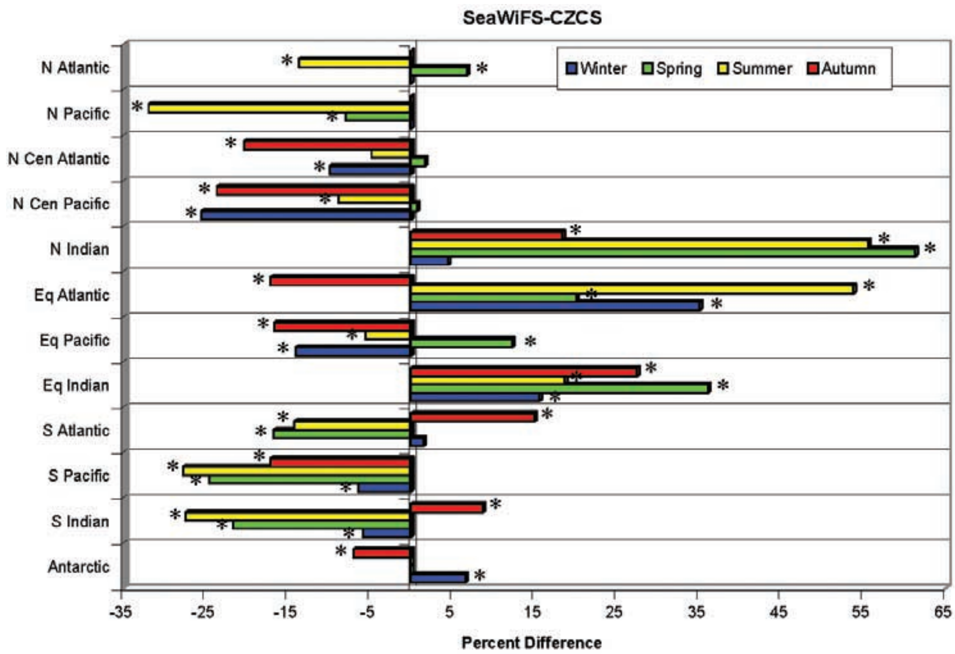

Figure 1. Seasonal differences between blended SeaWiFS and blended CZCS chlorophyll in the 12 major oceanographic basins [*Gregg et al.*, 2002]. Equatorial basins are between −10° and 10° latitude, the North Pacific and North Atlantic are north of 40°, and Antarctic is south of −40°. The other basins fall within these limits. Differences are expressed as blended SeaWiFS-blended CZCS. An asterisk indicates the difference is statistically significant at P < 0.05.

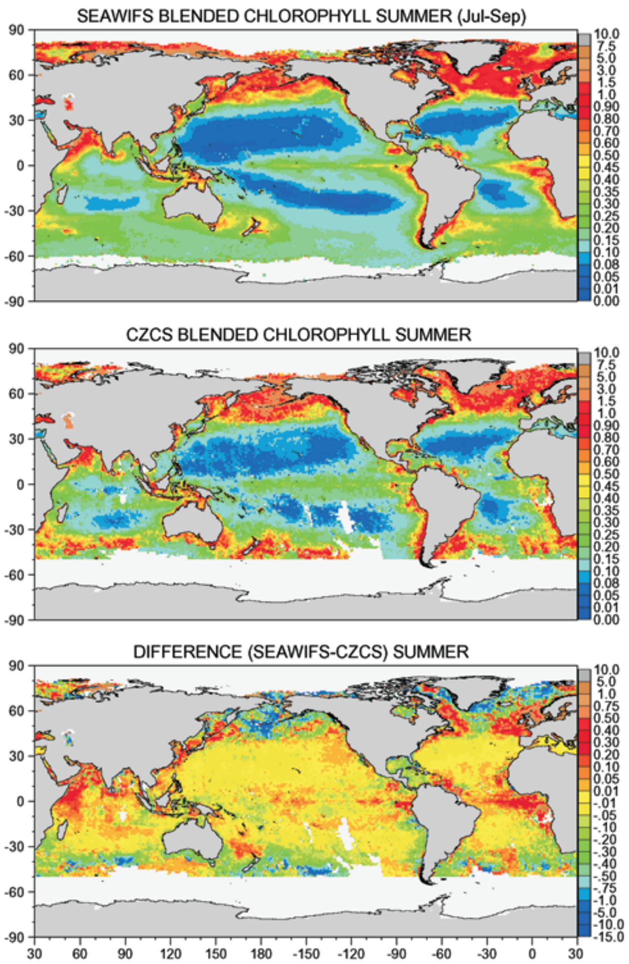

Figure 2. Summer (Jul–Sep) blended chlorophyll distributions for the SeaWiFS era (1997–2000), the CZCS era (1979-mid-1986), and the difference. Units are mg m^{-3}.

the central and northern portions of the basin (Figure 2). Partial compensation occurred in the eastern and western portions of the basin where chlorophyll increased (Figure 2).

[12] Moreover, the spring bloom peak changed in the present decade from the 1980's in the North Atlantic: the spring bloom peak was higher in the present decade and diminished more quickly (Figure 4). Warmer ocean temperatures produced accelerated mixed layer shoaling, and a higher spring bloom in a global modeling analysis [*Gregg*, 2002]. SST data for the North Atlantic indicated substantial warming since the 1980's: 0.6°C in spring and 0.8°C in summer. *Levitus et al.* [2000] observed a warming of about 0.4°C in the top 300 m in the extended North Atlantic basin (equator to pole) from the 1980's to 1997. Accelerated mixed layer shoaling and rapid phytoplankton growth associated with warming can exceed the ability of the zooplankton community to keep pace, leading to a larger bloom amplitude, and a more severe population crash as nutrients are exhausted [*Gregg*, 2002], as observed in the record here.

[13] In autumn the South Atlantic showed the opposite pattern as the rest of the Southern Hemisphere basins — it indicated a very large increase in chlorophyll in the recent decade (Figure 1). This increase was about 15% (Figure 1) and was mostly due to vastly higher chlorophyll concentrations along the South Atlantic sub-polar front and the Patagonian shelf (Figure 3).

[14] The plume on the Patagonian shelf and extending eastward had 54% higher chlorophyll concentrations in autumn in the recent decade. Local observations in the plume indicated 20% stronger winds than in the 1980's, deriving from a more northerly and westerly direction, i.e., directly from the land/shelf. SST's in the plume were 0.18°C colder. This evidence suggests that winds have increased in the SeaWiFS record and changed direction, which is driving upwelling and producing elevated chlorophyll concentrations that extend nearly across the South Atlantic.

[15] The global tropics represented an overall increase in chlorophyll concentrations from the 1980's to the present (Figure 1). This was especially true for spring and summer. Summer chlorophyll concentrations in the equatorial Atlantic represented one of the largest decadal changes in the global comparison (Figure 1). Much of the increase was due to vastly enhanced chlorophyll along the equator in the upwelling zone (Figure 2). The axis of the plume was accompanied by lower SST's (maximum change of about −0.1°C) suggesting increased upwelling. Additional con-

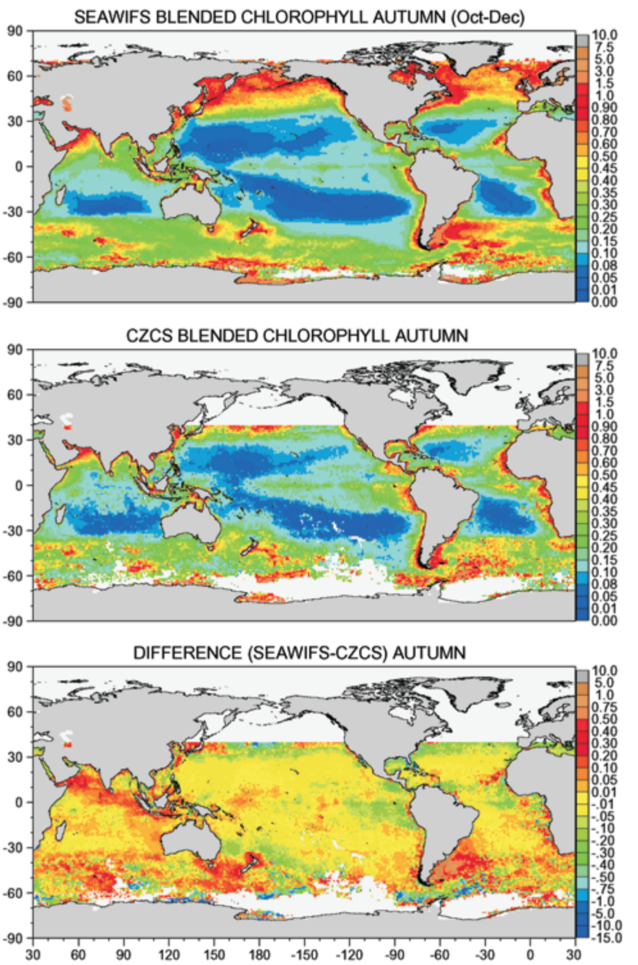

Figure 3. Autumn (Oct–Dec) blended chlorophyll distributions for the SeaWiFS era, the CZCS era, and the difference. Units are mg m^{-3}.

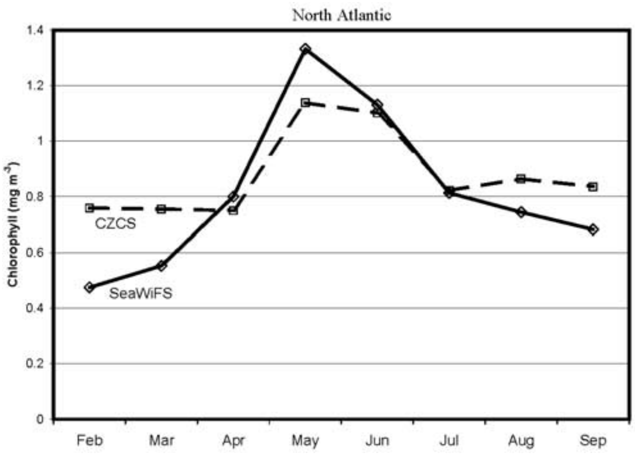

Figure 4. Monthly mean blended chlorophyll concentrations for the CZCS (squares, dashed line) and SeaWiFS (diamonds, solid line) for the North Atlantic.

tributions to increased blended SeaWiFS chlorophyll were from the Congo, Amazon, and Niger River outflows, which produced positive SST anomalies.

[16] Changes in the equatorial Pacific were mostly related to the relative over-representation of the 1997–2000 El Niño Southern Oscillation (ENSO) event [*Chavez et al.*, 1999] in the blended SeaWiFS data record. Although each observational time segment contained an equal number of El Niño and La Niña events (1 each), the duration of the total record (3.5 years and 7.5 years, for SeaWiFS and CZCS, respectively) changed their influence on the seasonal mean.

5. Summary

[17] The CZCS global ocean chlorophyll archive was reanalyzed using compatible atmospheric correction and bio-optical algorithms with SeaWiFS. This permitted, for the first time, a quantitative comparison of the decadal trends in global ocean chlorophyll from 1979- mid-1986 to the present (Sep 1997–Dec 2000). Blending of both archives with available coincident in situ data improved the residual errors of each data record and provided further compatibility. The analysis of the two chlorophyll records indicated large similarity in the global spatial distributions and seasonal variability. This included the extent and spatial structure of the mid-ocean gyres, the equatorial upwelling regions, and the bloom-recede dynamics of the high latitudes. There were also many decadal changes indicated in the analysis of the archives. Global chlorophyll concentrations indicated a decrease from the CZCS record to the present, of about −6%. Larger reductions occurred in the northern high latitudes. Conversely, chlorophyll in the low latitudes increased. Mid-ocean gyres exhibited limited changes. These results may indicate facets of climate change, some of which may be related to regional oscillation behavior such as the PDO and ENSO. Some of the decadal changes can be attributed to observed changes in SST or meteorological forcing, but some cannot. We believe that this reanalysis of the CZCS and SeaWiFS archives enables identification of some aspects of decadal change, and provides a marker of how the Earth's climate may be changing and how ocean biota respond.

[18] **Acknowledgments.** We thank the NASA/GES-DAAC for the Level-3 SeaWiFS data and Level-1A CZCS data (in particular James Acker), NOAA/NCEP for meteorological and SST data, Orbimage Corp. and the SeaWiFS Project for SeaWiFS data, NOAA/NODC archives and contributors (see Supplement[1]), and the NASA/SeaBASS archive and contributors (see Supplement[1]). We also thank J. E. O'Reilly (NOAA/NMFS), F. S. Patt (NASA/SAIC), and M. Wang (NASA/UMBC) for assistance in the CZCS reanalysis. We are grateful to S. Levitus (NOAA/NODC) for providing helpful comments on the manuscript. This work was supported by NOAA's Climate and Global Change Program, NOAA/NASA Enhanced Data Sets Element, Grant No. NOAA/RO#97-444/146-76-05 and the NASA Pathfinder Data Set Research Program.

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